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THEORIES OF MANURE AND FERTILIZER ACTION[1]

IT is to Liebig that we owe the first general theory of the nutrition of the plant and the function of fertilizers: although Liebig himself did not add anything to the knowledge of the process of carbon assimilation which had been acquired by Priestley, Senebier and others, nor to the study of the nitrogen and ash constituents which had been begun by de Saussure, he yet drew up from these facts a coherent theory of the course of nutrition and put it before the world with such vividness that it forthwith took its place in the general body of accepted scientific opinion. Liebig argued that since the ash constituents alone are drawn from the soil, it is only necessary, in order to ensure the complete nutrition of the plant, that there shall be no deficiency in the inorganic materials which are left behind when the plant is burnt. According to Liebig the function of the fertilizer is to supply to the soil the materials removed therefrom by the crop, and the fertilizer required can be ascertained beforehand by the analysis of a similar crop, so that the soil can be supplied with the exact amounts of potash, soda, magnesia, lime, phosphoric acid, etc., which would be removed by a normal yield of that particular crop. Neglecting Liebig's misconception of the source of the plant's nitrogen and the long controversy which arose as to the necessity of its artificial supply, we can restate the theory as assuming that

[1] A lecture given at the Graduate School of Agriculture, Cornell University, July, 1908.

the proper fertilizer for any particular crop must contain the amounts of nitrogen, phosphoric acid, potash and other constituents which are withdrawn from the soil by a typical good yield of the plant in question.

In this form the opinion, that the composition of the crop affords the necessary guide to its manuring, prevailed for some time and still survives in horticultural publications, but the course of field experiments, particularly those at Rothamsted, and the accumulation of farming experience soon demonstrated that it was a very imperfect approximation to the truth. Liebig's theory fails because it takes no account of the soil and of the enormous accumulation of plant food therein contained. Water-culture experiments demonstrated that certain elements, *e. g.*, sodium and silica, though universally present in the plant's ash, are unessential to its nutrition; field experiments also showed that other elements—magnesium, calcium, chlorine, sulphur, iron—though essential, are always supplied in sufficient quantities by all normal soils. Thus the elements to be supplied by the fertilizer became reduced to three—nitrogen, phosphorus and potassium—and even the amounts required of each of these are not indicated by the composition of the crop. To take an example—normal crops of barley and wheat would withdraw from the soil approximately the following fertilizing materials:

	Yield of Grain, Bushels	Pound per Acre Removed		
		Nitrogen	Phosphoric Acid	Potash
Wheat......	36	50	21	29
Barley......	48	49	21	36

Now the results of field experiments, which are abundantly confirmed by ordinary farming experience, go to show that the yield of wheat is chiefly determined by the supply of nitrogen; phosphoric acid is of secondary importance and only on exceptional soils will there be any return for the application of potash.

With barley, though its composition is very similar to that of wheat, the results are very different; nitrogen is still the most important element in nutrition, but phosphoric acid has equally marked effects, whilst in ordinary soils potash counts for little or nothing.

This may be illustrated from the Rothamsted experiments, and the part played by the reserves in the soil will be made evident by comparing the results obtained in the first and the fifth series of ten years.

AVERAGE YIELD OF BARLEY GRAIN, HOOS FIELD, ROTHAMSTED

Plot	Manuring	Average Yield of Grain, Bushels	
		First Ten Years, 1852–1861	Fifth Ten Years, 1892–1901
4 A	Complete fertilizer—Nitrogen, phosphoric acid, potash	46.1	36.3
3 A	Phosphoric acid omitted—Nitrogen and potash	35.0	22.1
2 A	Potash omitted—Nitrogen and phosphoric acid	45.6	28.0
1 A	Nitrogen only	33.6	16.6
4 O	Nitrogen omitted—Phosphoric acid and potash	30.5	12.8
1 O	Unmanured	22.4	10.0

The analysis of the barley plant would indicate that it requires nitrogen in the largest amounts, then potash and least of all phosphoric acid, but if the results for the first ten years of the experiment are considered it will be seen that the omission of either nitrogen or phosphoric acid from the fertilizer causes a big decline in yield in comparison with that of the completely fertilized plot. The omission of potash, however, is of little or no moment, since it only causes the yield to fall from 46.1 to 45.6 bushels per acre. Evidently the soil was able to supply all the requirements of the plant for potash despite the large

amounts which the crop removes. In the latter years of the experiment this stock of available potash in the soil had become somewhat depleted, so that the omission of potash from the fertilizer reduced the yield from 36.3 to 28.0 bushels per acre. The exhausted soil in these latter years causes the crop to respond to the constituents of the fertilizer only when they are all present together; taken singly, they increase the yield but little and the omission of any one of them reduces the crop almost to the minimum produced on the unmanured crop. The soil has thus become but a small factor in the nutrition of the crop, whereas as regards potash it was a very large one at the beginning of the experiment, and the defect of Liebig's theory was to neglect it entirely.

These differences in the manurial requirements of wheat and barley, differences which would not be apprehended from their respective compositions, may be correlated with the habits of growth of the two plants: wheat is sown in the autumn after but a slight preparation of the ground, nitrification is thus restricted, especially as the chief development of the plant takes place in the winter and early spring before the soil has warmed up, and as a consequence the crop is particularly responsive to an external supply of some active form of nitrogen. On the other hand, the wheat plant possesses a very extensive root system and a long period of growth, hence it is specially well fitted to obtain whatever mineral constituents may be available in the soil. In ordinary farming the only fertilizer used for the wheat crop will be a spring top-dressing of 100 pounds per acre or so of nitrate of soda or an equivalent amount of sulphate of ammonia or soot.

Barley is a spring-sown crop for which the soil generally receives a more thorough cultivation, in consequence of which and of the rising temperature there will be sufficient nitrates produced for the needs of the crop, often more than enough when the barley follows a root crop that has been liberally manured and perhaps consumed on the ground by sheep. But being shallow rooted and having only a short growing season, the plant experiences a difficulty in satisfying its requirements for phosphoric acid, hence the necessary fertilizer consists in the main of this constituent. Only on sandy and gravel soils, exceptionally deficient in potash and subject to drought, is any benefit derived from a supply of potash to the barley crop.

A still more noteworthy example is provided by the swede turnip crop; the analysis of a representative yield would show it to withdraw from the soil about 150 pounds per acre of nitrogen, 30 pounds of phosphoric acid and 120 pounds of potash. Yet the ordinary fertilizer for the swede crop will consist in the main of phosphatic material with but a small quantity of nitrogen and rarely or never any potash; for example, 400 pounds of superphosphate or 500 pounds of basic slag according to the soil (*i. e.*, 50 to 100 pounds of phosphoric acid), together with 12 to 15 pounds of nitrogen as contained in 50 pounds of sulphate of ammonia will form a very satisfactory mixture. The swede is sown late in the season after a very thorough preparation of the soil, so that the nitrification alone of the nitrogenous residue in the soil is capable of furnishing almost all the large amount of nitrogen it requires; it is very shallow rooted and must be supplied with an abundance of phosphoric acid. It was considerations of this kind which led Ville to suggest that for each crop there is a "dominant" fertilizing constituent, *e. g.*, nitrogen for wheat, phosphoric acid for swedes, and that the particular dominant is the constituent which the plant finds the most difficulty in appropriating from the soil, and hence which is therefore

more often indicated by a comparative deficiency instead of abundance in the ash of the plant. Such a theory is, however, not borne out by more general experiments; many plants do not exhibit such idiosyncrasies as are shown by wheat and swedes but require a general fertilizer the composition of which is determined more by the soil than by the plant. Indeed, no theory of manuring can be based upon the plant alone, but must also take the soil into account, so that a fertilizer may be regarded as rectifying the deficiencies of the soil as far as regards the requirements of the crop in question. What those special requirements are can only be decided by experiment, just as the soil conditions are ascertainable by trial rather than from *a priori* considerations of analysis. If an analysis be made of any soil in cultivation it will be found to contain sufficient plant food for the nutriment of a hundred or more full crops: the soil of the unmanured plot on the Rothamsted wheat field contained in 1893, after 54 years' cropping without fertilizer, 2,570 pounds per acre of nitrogen, 2,950 pounds of phosphoric acid and 5,700 pounds of potash. Of course much of this material is in a highly insoluble condition, but though attempts have been made by the use of weak acid solvents to discriminate between the total plant food in the soil and that portion of it which may be regarded as available for the plant, no proper dividing line can be thus drawn. The availability of a given constituent, say of phosphoric acid, will depend, as has already been seen, upon the nature of the crop; a given soil may contain sufficient easily soluble phosphoric acid for the needs of the wheat plant and yet fail to supply swede turnips with what they require. Again, the mechanical texture of the soil may be such as to limit the root range of the plant, so that a richer soil is necessary to produce the same result as is obtained in a poorer soil of more open structure; the state of the microflora of the soil may also have much to do with the amount of a given nutrient which can reach the plant.

Perhaps the best general point of view of the action of fertilizers is obtained by extending the "law of the minimum" originally enunciated by Liebig, according to which the yield of a given crop will be limited by the amount of the one particular constituent which may happen to be deficient; if the soil, for example, is lacking in nitrogen the yield will be proportional to the supply of nitrogen in the fertilizer, and no excess of other constituents will make up for the shortage of nitrogen. To take an example from the Rothamsted experiments, the following table shows the yield of wheat,

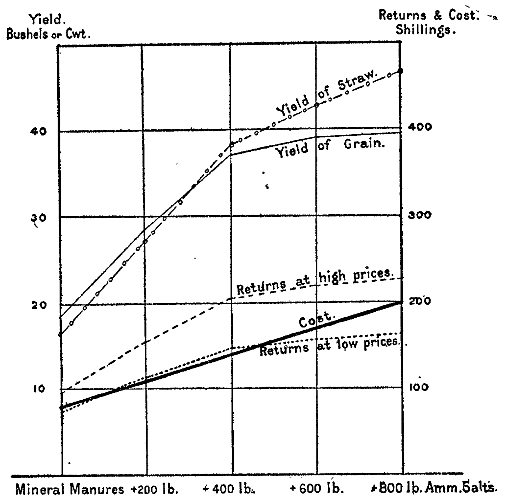
EXPERIMENTS ON WHEAT, BROADBALK FIELD, ROTHAMSTED

Averages over Thirteen Years (1852–64)

Plot	Manures per Acre	Dressed Grain		Straw	
		Produce per Acre	Increase for each Additional 43 lb. N in Manure	Produce per Acre	Increase for each Additional 43 lb. N in Manure
		Bush	Bush.	Cwt.	Cwt.
3	Unmanured	15.6	—	14.6	—
5	Minerals alone	18.3	—	16.6	—
6	" and 43 lb. N as ammonium-salts	28 6	10 3	27.1	10.5
7	Minerals and 86 lb. N as ammonium-salts	37.1	8.5	38.1	11.0
8	Minerals and 129 lb. N as ammonium-salts	39.0	1.9	42.7	4.6
16	Minerals and 172 lb. N as ammonium-salts	39.5	0.5	46.6	3.9

grain and straw, from the unmanured plot and from a series of plots, all of which receive an excess of phosphoric acid, potash, etc., but varying amounts of nitrogen, ranging from 43 pounds to 172 pounds per acre. That the nitrogen was deficient is shown by the almost negligible increase

produced by the mineral constituents without nitrogen; from this point the increase of yield is roughly proportional to the supply of nitrogen, until it reaches an excessive amount. The table also illustrates the generalization which is familiar to economists under the name of "the law of diminishing returns"—that the first expenditure of fertilizer or other factor of improvement is the most effective, each succeeding application producing smaller and smaller returns, until a further addition causes no increase in the yield. If the cost of the fertilizer, added to a prime outlay of 80 shillings per acre for the cultivation, and the value of the returns in cash, are expressed in the form of a diagram, the law is clearly expressed by the series of curves in the figure, where the cost of production forms a straight line that is always intersected by the curves expressing the value of the returns, which begin by rising more rapidly than the cost of production, but



Relation between cost of production and returns with varying quantities of manure

tend to become horizontal. The point of intersection when profit ceases is nearer the origin the lower the range of prices obtainable for the crop, as shown by the two curves representing the returns at low and high prices, respectively; this demonstrates that the expenditure on fertilizers or anything else required by the crop must be reduced when prices of produce are low, or, as expressed by the late Sir John Lawes, high farming is not remedy for low prices.

Liebig's law of the minimum must, however, be extended to all the factors affecting the yield as well as to the supply of plant food, *e. g.*, to such matters as the supply of water, the temperature, the texture of the soil. Any one of these may be the determining factor which limits the yield, or two or more of them may act successively at different periods of the plant's growth. On poor soils the water supply is very often the limiting factor, on very open soils because the water actually drains away, on extra close soils because the root range is so restricted that the plant has but little water at hand and the movements of soil water to renew the supply are very slow; in either case for comparatively long periods the plant will be sure to have as much nutriment as is required for the small growth permitted by the water present. It is only when the water supply is sufficient that the resources of the soil as regards all or any of the constituents of a fertilizer are tested, and may become in their turn the limiting factors in the growth of the crop. Hence it follows that fertilizers may often be wasted on poor land, where growth is limited by the texture of the soil, by the water supply or some other factor hardly controllable by the farmer: it is a truism that poor land can not be converted into good by manuring and that fertilizers give the best returns when applied to a good soil.

One fundamental difficulty still remains in considering the action of fertilizers: it has already been pointed out that a soil by no means notably fertile may contain

enormous quantities of plant food, which is, however, combined in so insoluble a form as to reach the plant in quantities insufficient for the requirements of the crop; for example, a soil may contain 0.1 per cent., or 2,500 pounds per acre, of phosphoric acid and yet yield a very indifferent swede crop unless it be supplied with an additional dressing of 50 pounds per acre of soluble phosphoric acid. It is usually assumed that the effect of this phosphoric acid manuring is due to the soluble nature of the fertilizer, because of which the additional plant food is directly available for the crop. But a little consideration of the reaction set up in the soil will show how insufficient such a theory must be; the phosphoric acid is very rapidly precipitated within the soil, as is shown by the fact that on many soils it remains close to the surface for many years and is never washed out into the drains. Bearing in mind this precipitation of the phosphoric acid in an insoluble condition, Whitney and Cameron proceed to argue that previous to the addition of the fertilizer a certain amount of phosphoric acid exists in solution in the soil water, this amount being in equilibrium with the various phosphates of calcium, iron, aluminium, etc., making up the great store of phosphates in the soil. This particular state of equilibrium would be but little disturbed by the addition of the soluble fertilizer in quantities which are small compared with the great mass of undissolved phosphates in contact with the soil water; the added phosphoric acid would only displace an almost equivalent amount of the phosphoric acid already in solution, and the concentration of the new solution would only differ from the old in the same degree as the ratio the phosphoric acid in the soil plus fertilizer (2,500 + 50 pounds of phosphoric acid) bears to the phosphoric acid originally in the soil (*i. e.*, 2,500 pounds phosphoric acid). In other words, before the fertilizer was added the soil water was as fully saturated with phosphoric acid as the amount of calcium, iron, aluminium and other bases would permit, and as these bases are present in enormous excess, the soil water must remain at the same saturation point after the fertilizer has been added, just as water will only hold 35 per cent. of the common salt in solution with however large a quantity of salt it may be in contact. Just in the same way the soil contains certain double silicates of which potassium is a constituent and these hydrolize to a slight extent in contact with the soil water, to yield a solution containing potassium ions. The addition of a soluble potassium salt, as in a fertilizer, will diminish the dissociation and therefore the solubility of the double silicate, the potassium of which is thrown out of solution until, as Whitney and Cameron argue, no more potassium ions remain in solution than were present before the addition of the fertilizer.

According to this point of view, the concentration of the soil water for a given plant food, such as phosphoric acid, must be approximately constant for all soils of the same type, however much or little phosphatic fertilizer may have been applied, and since water-culture experiments show that this low limit of concentration attained by the soil water is more than sufficient for the needs of the plant, no soil can be regarded as deficient in this or any other element of plant food. It therefore follows that the action, if any, of a fertilizer must be due to some other cause than the direct supply of plant food, with which the soil water must always be saturated to a degree which is quite unaffected by the supply of fertilizer.

This view of the interactions between the sparingly soluble phosphates of the soil, the soil water and the added soluble fertilizer,

can hardly be regarded as valid in theory, even if the conditions under which the reagents exist in the soil are the same as those which prevail in the laboratory when such conditions of equilibrium between sparingly soluble solids and water are worked out. It has no bearing whatever on the amount of nitrates in the soil water, since they come into a dissolved state as fast as the nitrifying bacteria produce them, and are not in equilibrium with any store of undissolved nitrates in the background. As regards phosphoric acid the theory assumes such an excess of bases that all soils behave alike and immediately precipitate the phosphoric acid, in practically the same form; while as regards potash the argument seems to forget that though the addition of a soluble potassium salt may throw some of the other sparingly soluble potassium compounds out of solution, the total amount of potassium remaining in solution is still greatly increased. The function of the carbonic acid in the soil water is ignored, as again the fact that the processes of solution in the soil must be in a constant state of change, so that it is the dynamic rather than the static solubility which is of importance. The soil is too complex a mixture to permit as yet of attaching great weight to theoretical deductions as to the actions taking place in it, and that the state of affairs postulated by Whitney and Cameron does hold in the soil has not however, been verified by experiment; the analyses, given by the authors of the theory, of the cold water extracts from a number of soils show great variations in their concentration, in nitrates, phosphoric acid and potash; nor is any evidence forthcoming that such concentrations are not immediately raised by the addition of fertilizers. Indeed, when the Rothamsted soils, with their long-continued difference in fertilizer treatment, are extracted with water charged with carbon dioxide, the nearest laboratory equivalent to the actual soil water, the amount of phosphoric acid going into solution is closely proportional to the previous fertilizer supply, and this proportionality is maintained if the extraction is repeated with fresh solvent, as must be the case in the soil. In the field it is not merely the initial concentration of the soil water in plant food which determines the supply of nutriment to the crop, it is also the capacity of the soil to keep renewing the solution as the plant withdraws from it the essential elements.

In one essential respect again the conditions prevailing in the soil are very different from those of the laboratory; in the soil all reactions are extremely localized, since they take place in the thin film of water normally surrounding the soil particles, in which movement of the dissolved matter takes place very slowly and mainly by diffusion. Of the extreme slowness of the diffusion of soluble salts in the soil the Rothamsted experiments afford some good examples; for instance, on the grass plots only an imaginary line divides the pots receiving different fertilizers, the manure is sown right up to the edge of the plot, a screen being placed along the edge to prevent any being thrown across the boundary, then immediately on the other side of the boundary the different treatment begins. In two cases plots receiving very large amounts of soluble fertilizer, *e. g.*, 550 pounds per acre of nitrate of soda or 600 pounds per acre of ammonium salts, march with plots receiving either no fertilizer or a characteristically different one, yet in neither case is there any sign in the herbage of the soluble fertilizer having diffused over the boundary. Although the treatment has been repeated now for 52 years, the dividing line between the two plots remains perfectly sharp and the rank herbage produced by the excess of nitro-

genous fertilizer on one side does not stray six inches over the boundary. Again, on the Rothamsted wheat field the plots are 20.7 feet in breadth and were separated by unfertilized strips only about a foot in breadth; in 1893 each plot was sampled down to a depth of 7.5 feet and the amount of nitrates was determined in each successive sample of nine inches in depth. The amount of nitrates found was in each case characteristic of the supply of nitrogen to the surface of the plot, and right down to the lowest depth there were no signs of the proportions approximating to a common level, as they would have done had any considerable amount of lateral diffusion been taking place. Considering that the plots are only separated by a foot or so of soil and each had been receiving its particular amount of nitrogen for forty and in some cases for fifty years, the sharp differentiation of plot from plot in the amount of nitrates at a depth of seven feet is sufficiently remarkable and is evidence that the movements of the soluble salts in the soil are confined to up and down motions due to percolation and capillary uplift, and take place laterally only to an insignificant extent.

From these considerations we may conclude that when a fertilizer is mixed with the soil each particle will establish round itself a zone of a comparatively concentrated solution to which the plant's roots will be drawn by the ordinary chemiotactic actions, and that these zones will extend but a little way into the generally much less dilute mass of the soil water, because of the slowness of the diffusion process.

That some such state of things prevails in the soil may be surmised from the common farming experience of the benefits derived from sowing the fertilizer close to the seed in such a case as superphosphate and turnip seed, where the fertilizer is not injurious to germination and the young plant is specially dependent on being rapidly pushed into growth in the early stages. Again, the intimate way in which the feeding fibrous roots of a plant will surround and cling to a fragment of fertilizer in the soil, such as a bone or a piece of shoddy, shows that some other actions are at work in the soil than the mere feeding of the plant upon the nutrients contained in the soil solution.

Whitney and Cameron's theory also supposes that the plant itself exerts no solvent action, whereas it has often been supposed that the roots excrete substances of an acid nature which exert a solvent action upon the soil particles. In this direction an experiment of Sachs's has become classical: he took a slab of polished marble and set it vertically in a pot of soil in which beans or some kindred plants were grown. After the plants had been growing for some time the contents of the pot were turned out and the slab of marble washed, whereupon the polished surface was found to be etched wherever the roots had been growing in contact with it. A polished slab of gypsum similarly treated shows a raised pattern wherever the roots have protected the surface from the solvent action of the general mass of water in the soil. Although Sachs himself attributed the etching to the action of the carbon dioxide which is always being given off by the roots, it has also been set down to fixed acids excreted by the root hairs, and determinations have been made of the acidity of the sap of the roots with the idea of differentiating between the solvent power of various plants. The roots of germinating seedlings are also found on occasion to redden blue litmus paper and undoubtedly may excrete substances of an acid character, but the behavior of seedlings, which are building up their fresh tissue out of the broken-down reserve materials contained in the seed, is essen-

tially different from that of plants leading an independent existence, so that nothing is thereby proved as to the source of the etching in Sachs's experiments.

Czapek instituted a fresh series of experiments with smooth slabs prepared by floating on to glass plates mixtures of plaster of paris and various phosphates of calcium, iron and aluminium; since only the calcium phosphate was etched, most of the possible acids were excluded and the etching action of the plant's roots was restricted to carbon dioxide or acetic acid. This latter was again excluded by a further experiment in which the slab was colored with congo red, and as this was not affected, the sole remaining solvent body the plant could have excreted was carbon dioxide. Again it has already been shown that water cultures containing nitrates, where the plant is growing in such solutions as exist under normal soil conditions, tend to become alkaline instead of acid, so that the balance of evidence is against the idea that plant roots excrete any fixed acids exerting a solvent action upon the soil particles. The carbon dioxide, however, probably exerts a considerable action, especially in the immediate vicinity of the root from which it is given off, for as it passes through the cell wall it must momentarily form a solution of considerable concentration, possessing a proportionally increased solvent power, and it is to this supersaturated solution that may be attributed the highly localized attack of the roots upon the soil particles. An experiment of Kossowitsch's illustrates the part played by the roots in attacking the insoluble materials in the soil: two pots of sand were prepared, each mixed with the same quantity of calcium phosphate in the form of ground rock phosphate; a third pot contained sand only. In this latter, and in one of the pots containing the calcium phosphate, seeds of mustard, peas and flax were sown. The growing plants were then furnished with a slow continuous supply of water containing appropriate amounts of nitrates, potash and other nutrient salts except phosphates. Before, however, this nutrient solution reached the pot containing the sand only it was made to percolate through the second pot containing sand and calcium phosphate, but it was applied directly to the pot containing calcium phosphate. In the pot containing calcium phosphate the growth was much greater than in the other pot, where the nutrient solution only contained what phosphoric acid it could dissolve in its passage over the calcium phosphate in the pot where nothing was growing, although this solution was continually renewed. The only factor determining the supply of phosphoric acid and the consequent difference in growth was the solvent action of the roots where they were actually in contact with the calcium phosphate, and this solvent action, as has already been shown, may most probably be attributed to the carbon dioxide excreted by the roots.

Following up their conclusions that the soil water possesses an approximately constant composition under all circumstances and always contains more of the constituents of plant food than would be required for the nutrition of the plant, Whitney and his colleagues have suggested another theory of fertilizer action. According to this point of view a soil falls off in fertility and ceases to yield normal crops, not because of any lack of plant food brought about by the continuous withdrawal of the original stock in the soil, but because of the accumulation of injurious substances excreted from the plant itself. These toxins are specific to each plant, but are gradually removed from the soil by processes of decay, so that if a proper rotation of crops be practised, to ensure that

the same plant only recurs after an interval long enough to permit of the destruction of its particular self-formed toxin, its yield will be maintained without the intervention of fertilizers. The function of fertilizers is to precipitate or to put out of action these toxins, and various bodies such as lime, green manure and ferric hydrate are also effective in this direction; the same result of destruction of the toxins excreted by the plant may even be brought about by minute quantities of certain bodies like pyrogallol. According to this theory the function of fertilizers is to remove toxins rather than to feed the plant; they are only required when the same crop is grown continuously and the need for them may be obviated by a judicious rotation which permits of the destruction of the toxins by natural causes. Careful consideration will show that this theory can be made to fit a good many of the phenomena of plant nutrition; it would also explain the difficulties experienced in growing certain crops continuously on the same ground; it is, in fact, an elaborated revival of one of the earliest explanations of the value of rotations, originally suggested by de Candolle. Furthermore, Whitney's colleagues have succeeded in extracting certain substances from the soil—oxystearic acid, pyridin derivatives, tyrosin, etc., which when introduced into water cultures are toxic to seedling plants. The compounds isolated are, however, all of them products of the oxidation and decay of proteins, fats and other compounds contained in plant residues; there is no evidence to show that they are specific excretions from particular plants or that they are more abundant in soil impoverished by the growth of a particular crop than in soil which would be usually termed rich. Again, it has not been demonstrated that such substances, although harmful to young plants in water culture, are toxic under soil conditions; it is well known how exceedingly sensitive are plants in water culture, where growth, for example, is inhibited by traces of copper not to be detected by ordinary methods of analysis. A body like ammonia, itself a product of protein decay and present in the soil, is exceedingly toxic to water cultures, yet when applied to the soil it increases the growth of the plant. Turning to the fertilizer side of the theory, evidence is yet lacking to show that fertilizers in such dilute solutions as they form in the soil water can exert any precipitating or destructive action on such toxic substances as have been extracted from the soil; particularly it is the specific action of fertilizers which is difficult to explain. Why should substances so dissimilar as nitrate of soda and sulphate of ammonia exert the same sort of action on the same toxin? Why should phosphates cause all classes of plants to develop in one direction, or why should it be appropriate to the toxins of all plants on one particular type of soil, whereas potash answers on another soil type? Lastly, there is a lack of evidence for the fundamental thesis that the rotation will take the place of fertilizers and that the yield only falls off when a particular crop is grown continuously on the same land.

On the rotation field at Rothamsted the yield of wheat on the unfertilized plot has been remarkably maintained; for the last five courses (tenth to fourteenth of the whole series) it has averaged 26.2 bushels per acre, but it is below the yield of the fertilized plots on the Broadbalk field, which averaged 35.7, 32 and 39.7 bushels for the same years, and also below the fertilized plot on the same rotation field, which averaged for the same period 37.1 bushels per acre, although the fertilizer is only applied once in four years to the swedes, which are followed by barley and either clover or a bare fallow before the turn of the wheat comes round. But with

other crops than wheat no such maintenance of yield is to be seen on the unfertilized plot of the rotation field—the barley yield has been reduced to 15.8 bushels against 27.7 on the fertilized plot, the clover yield to 940 pounds against 3,780 pounds on the fertilized plot, and the turnips to as little as 1,600 pounds against 40,000 pounds on the fertilized plot. Here we see that with the barley, clover, and particularly with the turnip crop, a rotation is quite unable to do the work of the fertilizer, the yield of turnips is reduced to a minimum on the impoverished soil, even though the crop only comes round once in four years and then grows so poorly that it can do little specific excretion to harm the succeeding crop. Many instances could be given of the incapacity of certain plants to grow in soil the fertility of which had been exhausted by other crops; for example, at Rothamsted in 1903 swede turnips were sown on Little Hoos field, which was known not to have been cropped with swedes or any kindred crop for more than forty years—and the average yield from thirty-two unmanured plots was only 9.3 tons per acre, although an exceptionally good start was made by the plant. In the following season barley was grown and the unmanured plots averaged 24.2 bushels per acre, a relatively much higher yield than the swedes had shown—yet barley had been repeatedly grown on the field in the years immediately before it was brought under experiment.

As it stands at present Whitney's theory must be regarded as lacking the necessary experimental foundation, no convincing evidence has been produced of the fundamental fact of the excretion of toxic substances from plants past the autotrophic seedling stage, nor is there direct proof of the initial supposition, that all soils give rise to soil solutions sufficiently rich in the elements of plant food to nourish a full crop did not some other factor come into play. If, however, we give the theory a wider form, and, instead of excretions from the plant, understand débris of any kind left behind by the plant and the results of bacterial action upon it, we may thereby obtain a clue to certain phenomena at present imperfectly understood. The value of a rotation of crops is undoubted and in the main is explicable by the opportunity it affords of cleaning the ground, the freedom from any accumulation of weeds, insect or fungoid pests associated with a particular crop, and to the successive tillage of different layers of the soil, but for many crops there remains a certain beneficial effect from a rotation beyond the factors enumerated.

The Rothamsted experiments have shown that wheat can be grown continuously upon the same land for more than fifty years and that the yield when proper fertilizers are applied remains as large in the later as in the earlier years of the series, any decline that is taking place is hardly outside the limits of seasonal variation and can easily be accounted for by the difficulties of tillage and the increase of one or two troublesome weeds. Mangolds again in the Rothamsted experiments show no falling off in yield, though they have now been grown upon the same land for thirty-two years, but with the barley crop, despite the application of fertilizers, there is a distinct secular decline in the yield. Again, it was found impossible to obtain satisfactory crops of swede turnips upon the same land for more than ten or twelve years in succession, and clover is well known to render the land "sick" for its own renewed growth for a period of from four to eight years on British soil. In this last case the persistence of the resting stages of the *sclerotinia* disease in the land may be the determining factor, but there are other crops, *e. g.*, flax, hemp and strawberries, which are considered by the practical cultivator to render the land more or less "sick," so that their

growth can not profitably be renewed until an interval of some years has elapsed.

Again it is well known that when a plant is sown upon land which has not carried that particular crop for many years beforehand it starts into growth with a vigor it rarely displays upon land where it forms an item in the regular rotation, even though the new land is so impoverished that the final yield is indifferent. In the instance quoted above, where swedes were sown on Little Hoos field, Rothamsted, after a very long interval, although the yield was poor on the unmanured plots, yet the seeds germinated and made their early growth in a very remarkable fashion, incomparably better than did the same seed sown upon adjoining land in a high state of fertility, but which had been cropped with swedes from time to time previously. There is thus some positive evidence that most plants—some to a very slight degree, like wheat and mangolds, others markedly, like clover, turnips, and flax—effect some change in the soil which unfits it for the renewed growth of the crop. The injurious action may even arise from the growth of a different crop, as in the well-known experiments at the Woburn Fruit Farm, where Pickering has shown that the roots of grasses exert a positively injurious effect, distinct from competition for food, water or air, upon fruit trees growing in the same soil.

Assuming that the persistence in the soil of obscure diseases appropriate to the particular plant can be neglected as the cause of these phenomena, there still remains some unexplained factor arising from a plant's growth which is injurious to a succeeding crop, and this may either be the excreted toxins of Whitney's theory or may be some secondary effects due to the competition of injurious products of the bacteria and other microflora accumulating in the particular soil layer in which the roots of the crop chiefly reside.

Experimental evidence is as yet wanting as to these highly complex interactions between the higher plants and the microflora of the soil, but Russell and other observers have shown how greatly a disturbance of the normal equilibrium of the flora of the soil may affect its fertility, as measured by the yield of a higher plant. Partial sterilization, such as is brought about by heating the soil to 98° for ten hours, will double the yield of the succeeding crop and will show a perceptible beneficial effect up to the fourth crop after the heating, and exposure to the vapors of volatile antiseptics like toluene or carbon bisulphide, which are afterwards entirely removed by exposure, will increase the yield in a similar but smaller degree; even drying the soil appears to have an influence upon its fertility.

It is in this direction, perhaps, that the clue may be found to the unexplained benefits of the rotation of crops, and to some of the other facts difficult of explanation upon the ordinary theories of plant nutrition, which have been advanced by Whitney and his co-workers. The soil, however, is such a complex medium—the seat of so many and diverse interactions, chemical, physical and biological—and is so unsusceptible of synthetic reproduction from known materials, that experimental work of a crucial character becomes extremely difficult and above all requires to be interpreted with extreme caution and conservatism.

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THE DUBLIN MEETING OF THE BRITISH ASSOCIATION—II.

The Metabolism of the Plant Considered as a Catalytic Reaction[1]

After outlining the three fundamental principles of reaction-velocity, the law of

[1] Address by Professor F. F. Blackman, M.A., F.R.S., president of the botanical section, on "The Manifestations of the Principles of Chemical Mechanics in the Living Plant."